(12) UK Patent Application (19) GB (11) 2 307 332 (13) A

(43) Date of A Publication 21.05.1997

(21) Application No 9523518.0

(22) Date of Filing 17.11.1995

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(51) INT CL^6
H01S 3/131

(52) UK CL (Edition O)
H1C CEX C208 C213 C239 C30Y C35Y C391 C392 C400 C401 C403 C660 C666 C669 C671 C674 C739 C78Y C782 C783 C784

(56) Documents Cited
Proceedings of the 1992 IEEE Frequency Control Symposium, 27-29 May 1992, pages 420-424.

(58) Field of Search
UK CL (Edition O) H1C CA CEX CX
INT CL^5 G02F 1/35 , H01S 3/13 3/131 3/133 , H04B 10/145
ONLINE: CLAIMS, INSPEC, JAPIO, WPI

(54) Optical frequency synthesiser

(57) The frequency synthesiser includes an optical delay line 322 delaying one optical signal from a coupler 310 relative to a second optical signal. The optical signals are obtained by mixing radiation from two lasers 304, 306, in the coupler 310, optionally after adjustment at 309 of the polarisation of the radiation from one of the lasers. The optical signals are converted to electrical signals by diode detectors 318. From the phase difference between the resulting signals, a negative feedback signal, which is used to control the difference frequency of the lasers is obtained. The output frequencies of the synthesiser are preferably less then 100GHz and may be continuously variable. The optical delay line may be optical fibre which is stabilised against length change due to temperature. The lasers may be Nd:YAG.

Figure 1

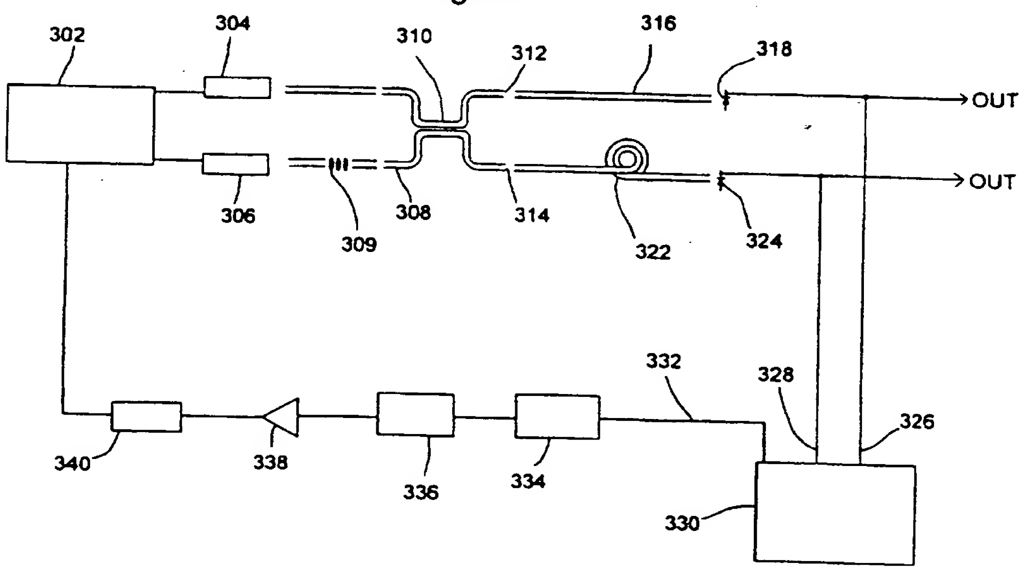

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Figure 1

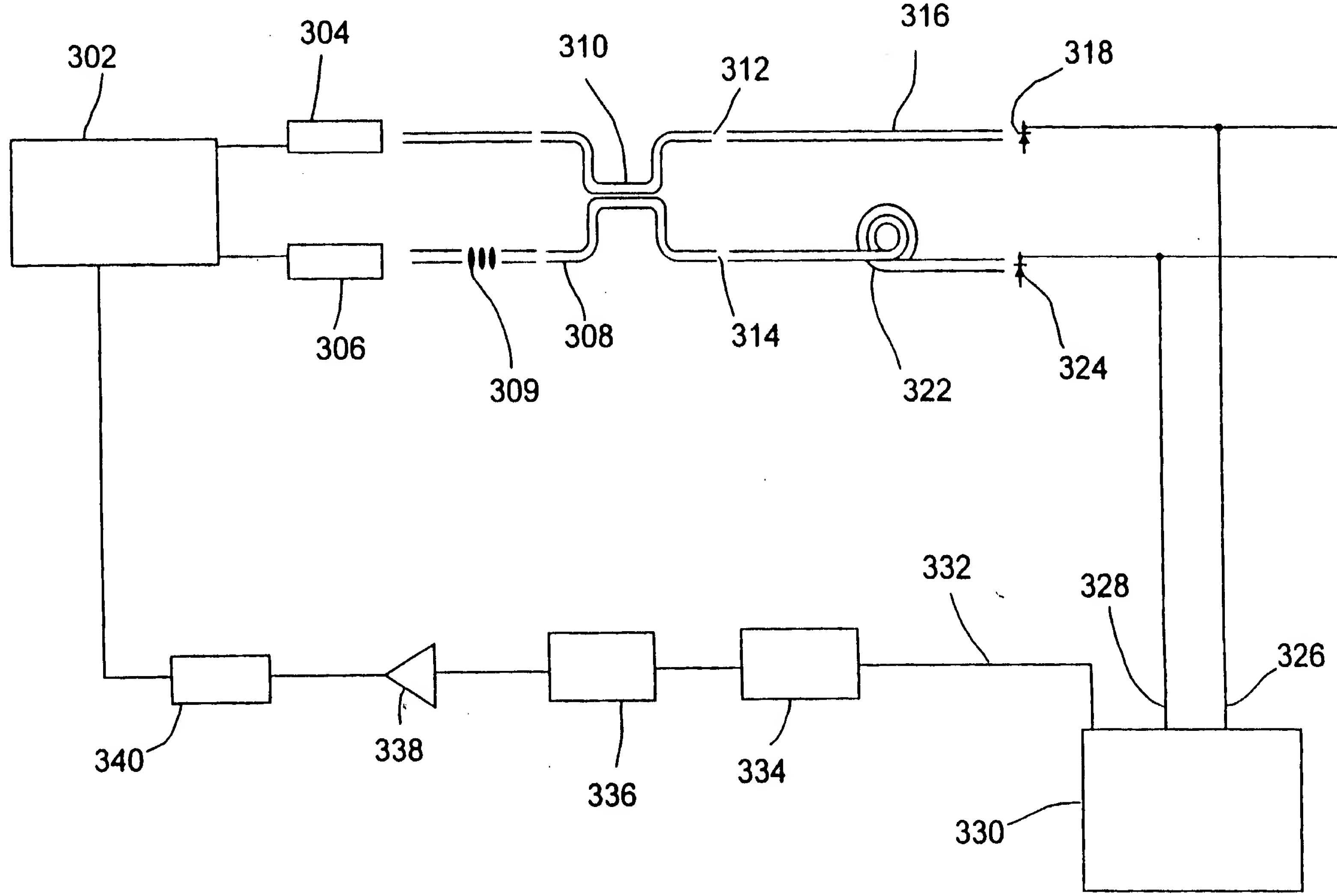
302
304
306
309
308
310
312
314
316
318
322
324
OUT
OUT
326
328
330
332
334
336
338
340

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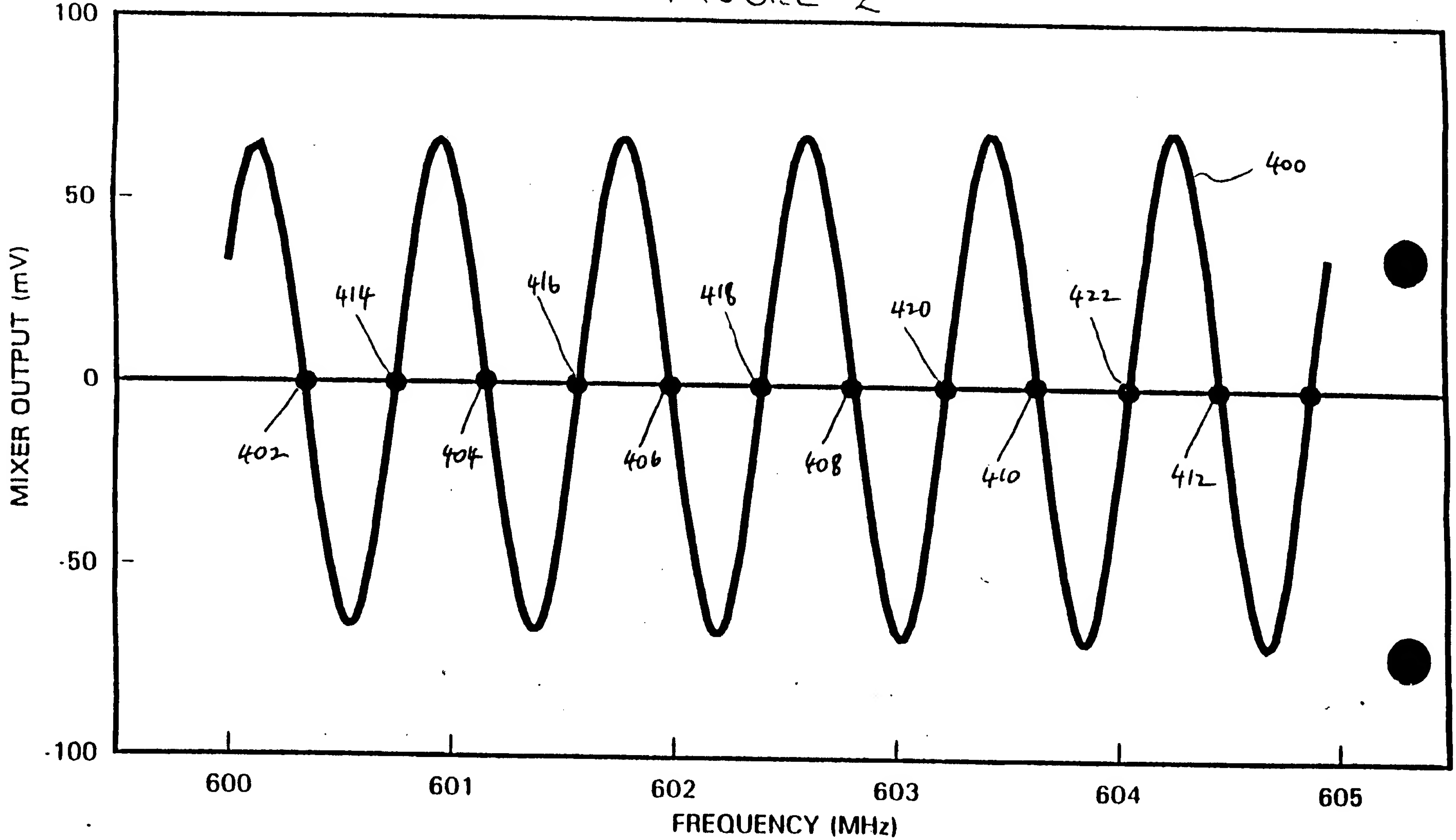
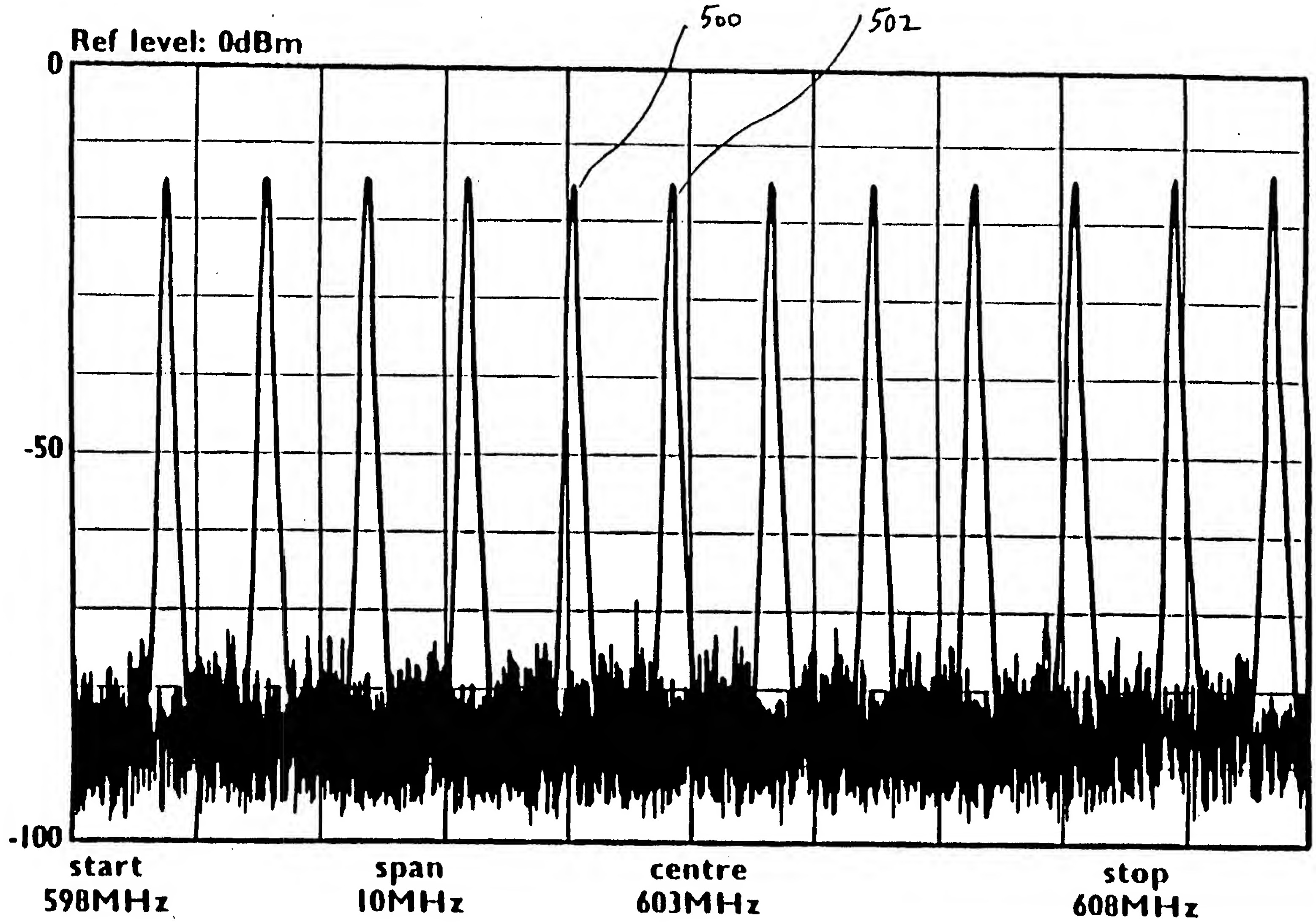
FIGURE 2



400
402
404
406
408
410
412
414
416
418
420
422
100
50
0
-50
-100
MIXER OUTPUT (mV)
600
601
602
603
604
605
FREQUENCY (MHz)

FIGURE 3


Ref level: 0dBm
0
-50
-100
500
502
start
598MHz
span
10MHz
centre
603MHz
stop
608MHz

FREQUENCY SYNTHESISER

This invention relates to frequency synthesisers and their stability. Fluctuations in phase of an oscillator can also be interpreted as frequency fluctuations, and in this document no distinction is made between frequency and phase fluctuations. This phase/frequency relationship is described in "Frequency Analysis Modulation and Noise", Chapter V, Modulation, by Stanford Goldman, McGraw-Hill (1948).

Frequency synthesisers are well known devices which are arranged to provide an output signal which has a frequency selected from a discrete set of values. Frequency synthesisers may use a frequency discriminator to maintain the stability of the selected frequency of the output signal.

An example of a simple frequency discriminator is shown in "Electricity and Magnetism" by B.I.Bleaney and B.Bleaney, page 581, Third Edition, Oxford University Press 1983. This device is an LC circuit discriminator, where L and C are circuit components having inductance L and capacitance C respectively. An oscillator output signal is input to the discriminator, which produces an output signal dependent on the input frequency, and thus can be used to control the oscillator output frequency in a feedback control loop. Such a discriminator is suitable for operation at a single frequency only. It is not suitable for use with a multi-frequency synthesiser.

Frequency discriminators are known for use in feedback control loops. Feedback control loops are systems in which an output signal is fed back into an input of the system to modify the system characteristics. In such feedback systems, "positive feedback" occurs if the signal fed back to the input causes an increase in output signal as occurs in oscillators; and "negative feedback" occurs if it causes a decrease in output signal. Negative feedback effects are used to stabilise circuits such as amplifier circuits.

Such discriminator feedback loops are known for use in stabilising outputs from frequency sources: such as voltage controlled oscillators (VCOs). However, changes in ambient temperature can result in drifting of the values of impedance and capacitance of the components of prior art frequency discriminators. This can cause the output of the frequency discriminator to drift and consequently the output frequency of the source can drift.

A further form of VCO involves the use of two high frequency oscillators, at least one of which is tuneable, to produce a tuneable output beat frequency. The VCO may comprise two lasers, whose radiation is mixed to produce a microwave beat frequency. The effect of temperature drift is particularly pronounced for sources based on laser mixing. The frequency of radiation from a laser operating at 1.3 μm is approximately 3×10^{14} Hz, and a drift of only one part per million can result in changes in beat frequency of 300 MHz. Drifts of this magnitude can be a significant proportion of the intended operating microwave frequency of the source, and thus are undesirable, and even intolerable, when used in a system requiring a stable frequency source.

A fibre-optic stabilised electronic oscillator is described by R.T.Logan, Jr. et al. in the Proceedings of the 45th Annual IEEE Frequency Control Symposium, pp 508-512, 1991. The Logan device comprises a VCO having an output which is passed to a fibre-optic discriminator which in turn provides a frequency control to the VCO via a loop filter. The fibre-optic discriminator splits an RF input signal into two, one part of which is converted to a modulated optical signal and delayed using a fibre-optic delay line and then converted back to an electrical signal by a photodiode receiver and one part of which is passed through a phase shifter. The two parts are then compared by a phase detector which outputs a voltage dependent on the phase difference between the two parts. The fibre-optic delay line comprises a laser diode producing a modulated optical signal which is fed to a length of single-mode optical fibre. The performance of the Logan device is limited by the fibre-optic discriminator noise. The Logan paper suggests that the system may be improved by the use of diode pumped solid-state lasers and external intensity modulators in order to increase the signal to noise ratio.

The Logan device suffers from the disadvantage that in order to use a fibre optic delay line to stabilise an oscillator. the RF oscillator signal must be converted from an electrical signal to an optical signal and thence back to an electrical signal.

It is an object of the invention to provide an alternative form of frequency synthesiser.

The present invention provides a frequency synthesiser for providing an output signal comprising:

(a) source means for generating two modulated optical signals. the optical signals having a modulation frequency;

(b) means for delaying one of the modulated optical signals relative to the other; and

(c) control means for controlling the source means in response to a modulation phase difference between the relatively delayed modulated optical signals.

The use of means for delaying an optical signal allows for frequency synthesisers to be made which are physically smaller than corresponding synthesisers with conventional delay lines such as co-axial cables. The invention provides the advantage over the Logan device that the synthesiser does not require the conversion of an electrical signal to an optical signal.

The invention may be used for controlling the output frequencies from HF to millimetric radiation generated by the mixing of radiation from two lasers. HF radiation has a frequency in the range from 3 MHz to 30 MHz.

In a preferred embodiment the frequency synthesiser means includes fibre optic delay means. The combination of wide bandwidth of mixed laser radiation with high degree

of phase stability and the wide bandwidth capability of the optical fibre delay means enables the frequency of the mixed radiation to be tuned and stabilised over a wide range of frequencies.

Prior art frequency synthesisers incorporating a feedback loop suffer from the disadvantage that to achieve high precision a high gain is required in the feedback loop. This requirement is reduced when using lasers in the synthesiser of the invention because of the great sensitivity of the beat frequency to a small fractional change in the frequency of one laser.

An embodiment of the invention will now be described, by way of example only, with reference to the drawings, in which:

Figure 1 is a schematic diagram of a frequency synthesiser of the invention arranged to control the frequency of a mixed laser source;

Figure 2 is a graph of the variation with frequency of a phase detector output of the Figure 1 synthesiser;

Figure 3 is a composite graph showing twelve separate output spectra of the Figure 1 synthesiser.

Referring to Figure 1, there is shown a frequency synthesiser of the invention arranged to control a mixed laser radiation source configured as an RF/microwave frequency synthesiser, the synthesiser being indicated generally by 300. A Laser Offset and Locking Accessory (LOLA) unit 302 is connected to two lasers 304 and 306. The LOLA unit 302 is a series 2000 LNC unit made by Lightwave Electronics. It is a power supply for the lasers 304 and 306 and in certain operational modes also acts to lock their difference in frequency to a reference oscillator. The lasers 304 and 306 are Lightwave Electronics devices, diode-pumped Nd:YAG models 123-1319-040-F-W

and -B-W respectively. They have peak powers of 40 mW and a maximum frequency separation of 100 GHz.

Radiation from the lasers 304 and 306 is directed to a 50/50 directional coupler 308. Radiation from the laser 306 passes through a polarisation controller 309 and subsequently to the coupler 308. The coupler 308 has a central portion 310 comprising two coupled optical fibres, and two outputs 312 and 314. The radiation from the lasers 304 and 306 is combined by evanescent coupling in the central portion 310.

The combined radiation output from output 312 is transmitted to an optical fibre 316 and thence to a radiation detector 318. The detector 318 is a reverse biased PIN diode. The combined radiation output from output 314 passes through a delay line 322. The delay line 322 is a 250 metre length of optical fibre, providing a propagation delay of approximately 1.2 μs. The optical fibre forming the delay line 322 is cladded for improved temperature stability. A second radiation detector 324 is located at an end of delay line 322 remote from output 314 of coupler 308. The detector 324 is a reverse biased PIN diode identical to detector 318. The output of the synthesiser 300 may be taken from either or both of detectors 318 and 324. For clarity of illustration, electrical connections to the detectors 318 and 324 are not shown.

For the mixed laser outputs to give outputs from the detectors 318 and 324 at the beat frequency, it is necessary for the coupler 308 to receive radiation from the two lasers 304 and 306 having the same polarisation. The polarisation controller 309 is included so that the polarisation of light from the laser 306 matches that from the laser 304. The intensity of the detector RF outputs are monitored and the polarisation of the radiation from the laser 306 reaching the coupler 308 adjusted using the polarisation controller 309 so as to maximise this intensity.

Signal outputs from detectors 318 and 324 are connected to input ports 326 and 328 respectively of a phase detector 330. The phase detector 330 is a dc coupled ANZAC

MD141 mixer. It has an output 332 connected via two 10 dB attenuators 334 and 336, an amplifier 338 and a 5.1 kΩ resistor 340 to the LOLA unit 302. The resistor 340 in combination with the capacitive input impedance of the LOLA unit 302 acts as a low pass filter.

If required, low noise amplifiers could be incorporated in the synthesiser 300 to amplify the signal outputs from the detectors 318 and 324 prior to the input ports 326 and 328.

The operation of the synthesiser 300 will now be described. The combining of the lasers in the 50/50 directional coupler 308 results in optical signals having an RF, micro- or millimetre-wave intensity modulation at the beat frequency of the lasers passing from the outputs 312 and 314 to the optical fibre 316 and the delay line 322. The optical signal in each of the fibre 316 and the delay line 322 is converted to an electrical signal by the detectors 318 and 324 respectively. The signal output from the detector 324 is delayed in relation to the signal output from the detector 318 by a time approximately equal to the propagation time of the optical signal through the delay line 322. Consequently, if the modulation frequency of the output from the coupler 308 is varying with time, then the input signals to the phase detector 330 will vary in phase which will in turn result in a time varying output from the phase detector 330. The modulation frequency may vary with time due to a frequency drift in one or both of lasers 304 and 306.

If the modulation frequency is stable with time then the output of the phase detector will be constant in time. In particular, if the modulation frequency is stable with time and the frequency is such that the two inputs to the phase detector are in phase quadrature then the phase detector will produce a null output. "Phase quadrature" means that the signals have the same frequency and waveform but have a phase difference of $\pi/2$ radians.

Figure 2 shows a graph of the variation measured in the open-loop mode of the output of the phase detector 330 with output beat frequency over a range of several MHz. The output has a curve 400 of approximately sinusoidal form. The curve 400 has stable points 402, 404, 406, 408, 410 and 412 and unstable points 414, 416, 418, 420 and 422. The output from the phase detector 330 acts as a controlling voltage input signal to the LOLA unit 302 via attenuators 334 and 336, amplifier 338 and resistor 340. The frequency synthesiser 300 therefore includes a feedback system. If the frequency of mixed radiation is constant in time, and of appropriate value for negligible output from the phase detector 330, then the controlling input voltage signal to the LOLA unit 302 is also very small.

There now follows a simplified description of the operation of the feedback loop. If, for example, the modulation frequency corresponds to point 402 then the output of the phase detector 330 is zero and the output frequency of the synthesiser 300 remains at that frequency. If the modulation frequency drifts to a higher frequency then the response of the phase detector is to produce a negative voltage output. Consequently, the controlling voltage input signal to the LOLA unit 302 is also negative, causing the frequency separation between the output of the lasers 304 and 306 to be reduced, resulting in the modulation frequency decreasing back toward the frequency of the point 402.

Similarly, a decrease in the modulation frequency from point 402 causes the phase detector 330 to produce a positive voltage output. Consequently the controlling or correction voltage input signal to the LOLA unit 302 is positive. This causes the modulation frequency to be increased back towards the frequency of point 402. Thus at the frequency of point 402, any instability of the modulation frequency, whether an increase or a decrease, results in a negative feedback of the synthesiser 300 causing the output frequency to stabilise at a frequency close to that of the point 402. The foregoing consideration also applies when the synthesiser output is set to the other stable points 404 to 412.

Conversely, points 414 to 422 represent unstable points. If the modulation frequency is at the frequency of point 414, then an increase in modulation frequency results in the phase detector producing a positive voltage which increases the modulation frequency even further and stable operation is not possible. Instability at any of the points 414 to 422 results in positive feedback of the synthesiser 300 causing the output frequency to be driven away from an unstable point such as 414.

If the beat frequency of the mixed radiation deviates from a frequency corresponding to that of one of the stable points 402 to 412 then the phase detector 330 produces an output signal such as to change the frequency of one or both of lasers 304 and 306 to oppose the beat frequency fluctuation of the mixed radiation.

The synthesiser 300 has significant advantages over prior art frequency stabilising systems. In prior art systems the individual lasers are stabilised, whereas in the synthesiser 300 it is the beat frequency produced by the mixing of radiation from lasers 304 and 306 which is stabilised. Consequently only one parameter, the beat frequency, needs to be stabilised, whereas in known systems at least two parameters - the individual laser frequencies - need to be stabilised simultaneously.

The output frequencies of the lasers 304 and 306 can be adjusted by electrical control ports on the LOLA unit 302. Alternatively, the temperature of one laser 304 or 306 can be altered using the LOLA unit 302 thermal controls to change its frequency. The temperature changes induced are of the order of 1 GHz per degree celsius. A further option is for combined thermal and electrical control using the LOLA unit 302, in which the thermal controls are used for coarse frequency adjustment and the electrical controls for fine adjustments.

The optical fibres 316 and 322 of Figure 1 may be temperature-stable fibres. Temperature stable fibre is described by R.Kashyap et al. in Electronic Letters Volume 19 Number 24, 1983, pages 1039-1040. The use of temperature stable fibres enables the frequency of the output of the respective sources to be stabilised to a higher degree.

as changes in ambient temperature will have a reduced effect on the optical delay paths of the synthesiser 300. Alternatively, the fibres may be placed in a temperature controlled environment, or the optical path length may include an auxiliary temperature dependent path in series with the fibre in order to maintain a constant delay period.

The use of optical fibre 322 in the optical delay path of synthesiser 300 allows for a significantly higher effective quality factor, Q_F, to be obtainable than with prior art discriminators particularly at high frequencies. For propagation of 1.3 µm radiation, single mode optical fibre has a loss of approximately 0.4 dB per kilometre. Radiation at this wavelength takes approximately 5 microseconds to travel 1 kilometre in optical fibre, and consequently its attenuation is approximately 0.1 dB per microsecond. For a fibre in which a 3 dB loss is acceptable, this implies a propagation delay of 30 microseconds can be achieved.

The effective quality factor Q_F is given by the following approximate expression:

$$Q_F = \pi f \tau ,$$

where f is the frequency of radiation and τ the propagation delay. For X-band microwave radiation, at a typical frequency of 10 GHz, and a relative delay of 30 microseconds, Q_F is approximately 10^6, or one million. This is significantly higher than for prior art synthesiser systems, although such high Q-values will not necessarily be used in practice. This is because for high Q-values the output spectrum is only improved close to the centre frequency. The propagation delay τ also determines the separation of stable frequencies Δf since $\Delta f = 1/\tau$.

Figure 3 shows a graph of the output RF spectrum at various frequencies. Figure 3 is a composite graph of twelve discrete spectra, each spectrum having a single peak such as peaks 500 and 502 which are spaced in frequency by 0.8 MHz. 0.8 MHz is the reciprocal of the 1.2 µs time delay imposed by the optical fibre 322. The synthesiser

300 can be used to synthesise output frequencies at multiples of approximately 0.8 MHz.

The synthesiser 300 may be provided with tuning means for selecting a given synthesised output frequency. This may be done by means of an auxiliary coarse voltage control to the VCO which may control means for adjusting the temperature of one or both individual lasers. The operation of the feedback loop is to lock the frequency to one of the stable points of the discriminator response of Figure 2.

The synthesiser 300 allows a discrete set of output frequencies to be obtained by controlling the LOLA unit 302 to an approximate value and using the feedback loop to lock the frequency accurately to one of the stable values shown in Figures 2 and 3. Such a discrete frequency selection is valuable for many applications of synthesisers. for example as a local oscillator in an FM radio receiver where a channel spacing of for example 50 kHz is required. In other applications, it is desirable to have greater control over the output frequency. Finer frequency intervals, a continuous tuning capability, or a capability to produce an FM signal may be required. Such capabilities are readily achievable by minor modifications to the synthesiser 300 of Figure 1.

Access to the unstable frequencies 414, 416, 418, 420 and 422 of Figure 2 is readily achievable by inverting the sign of the output of the amplifier 338. If the amplifier 338 is a differential amplifier with two inputs, one of which is grounded, the sign of the output may be inverted by reversing the input connections.

A continuous frequency capability over a limited range may be provided by incorporating a differential amplifier prior to the amplifier 338. The differential amplifier may have a gain of unity and so would have a negligible effect on the operation of the synthesiser if its second input were to be grounded. However, if the second input is connected to a variable voltage V_2, the action of the feedback loop is to force the voltage from the phase detector towards V_2. From Figure 2, it may be seen that this provides a continuous tuning capability over approximately half the frequency

range. By additionally incorporating an inverting capability to the differential amplifier output, essentially continuous frequency coverage is possible. The application of an ac voltage as the input voltage V_2 would provide an FM capability. This FM capability would however be restricted to low frequencies as high frequencies would be suppressed by the low-pass filter action of the resistor 340 and the capacitive input impedance of the LOLA unit 302.

An alternative continuous tuning capability may be provided by incorporating an RF phase shifter before one or both of the input ports 326 and 328 of the phase detector 330. Altering the relative phases of the two inputs to the phase shifter 330 has the effect of shifting the curve 400 parallel to the x-axis.

A high frequency FM capability may be achieved by inserting a unity gain differential amplifier immediately prior to the input to the LOLA unit 302, i.e. after any low pass filter. Normally the effect of the feedback loop is to correct for any frequency modulation or instability in the output frequency. In this high frequency FM arrangement however, the correction signal to counteract the effects of the frequency modulation is suppressed by the low-pass filter.

The graph of Figure 2 shows a substantially sinusoidal output. It should be noted, however, that the waveform of frequency discriminator response to frequency changes is of only secondary importance in this invention. The most important parameters of the discriminator response are the frequencies at which the null points such as 402 to 422 occur, as these define the stable and unstable points for discriminator operation and the slopes at the stable frequencies.

In an alternative embodiment, the delay line 322 may be replaced by a suitably configured Fabry-Perot etalon to provide the necessary optical delay.

CLAIMS

1. A frequency synthesiser for producing an output signal comprising:

   (a) source means for generating two modulated optical signals, the optical signals having a modulation frequency;

   (b) means for delaying one of the modulated optical signals relative to the other; and

   (c) control means for controlling the source means in response to a modulation phase difference between the relatively delayed modulated optical signals.

2. A frequency synthesiser according to Claim 1 wherein the control means comprises:

   (i) two detectors, each for producing a respective detector output signal in response to a received modulated optical signal;

   (ii) a phase detector responsive to a phase difference between the detector output signals for producing an output in response thereto; and

   (iii) means responsive to the phase detector for adjusting the source means.

3. A frequency synthesiser according to Claim 2 wherein the phase detector provides a negative feedback signal to the means responsive to the phase detector.

4. A frequency synthesiser according to any preceding claim wherein the frequency synthesiser is arranged to provide an output signal having a frequency which is equal to the modulation frequency and less than 100 GHz.

5. A frequency synthesiser according to any preceding claim wherein the source means comprises:

   (i) two coherent optical sources, each for generating a respective radiation beam of respective differing frequency; and

   (ii) means for combining the two radiation beams to produce the two modulated optical signals.

6. A frequency synthesiser according to Claim 5 wherein the means for combining the two radiation beams is an optical fibre coupler.

7. A frequency synthesiser according to Claim 5 or Claim 6 wherein the coherent optical sources are lasers.

8. A frequency synthesiser according to Claim 7 wherein the lasers are Nd:YAG lasers.

9. A frequency synthesiser according to any preceding claim wherein the means for delaying one optical signal relative to the other is a length of optical fibre.

10. A frequency synthesiser according to Claim 9 wherein the length of optical fibre is stabilised against changes in length due changes in temperature.

11. A frequency synthesiser according to any preceding claim wherein the synthesiser includes means for providing a continuous tuning capability.

12. A frequency synthesiser according to any preceding claim wherein the output signal is frequency modulatable.

13. A frequency synthesiser substantially as herein described with reference to Figure 1.

The Patent Office

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Application No: GB 9523518.0
Claims searched: 1-13

Examiner: David Mobbs
Date of search: 9 February 1996

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.O): H1C CA, CEX, CX.

Int Cl (Ed.6): G02F 1/35; H01S 3/13, 3/131, 3/133, H04B 10/145.

Other: ONLINE: CLAIMS, INSPEC, JAPIO, WPI.

Documents considered to be relevant:

Category	Identity of document and relevant passage	Relevant to claims
X	Proceedings of the 1992 IEEE Frequency Control Symposium, 27-29 May 1992, pages 420-424, Logan R.T. Jnr. et al., Ultrastable microwave and millimeter wave photonic oscillators. See particularly page 423 and figure 3.	1-4, 9, 11.

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.